Measurement of Ionization Cooling with the MICE Experiment

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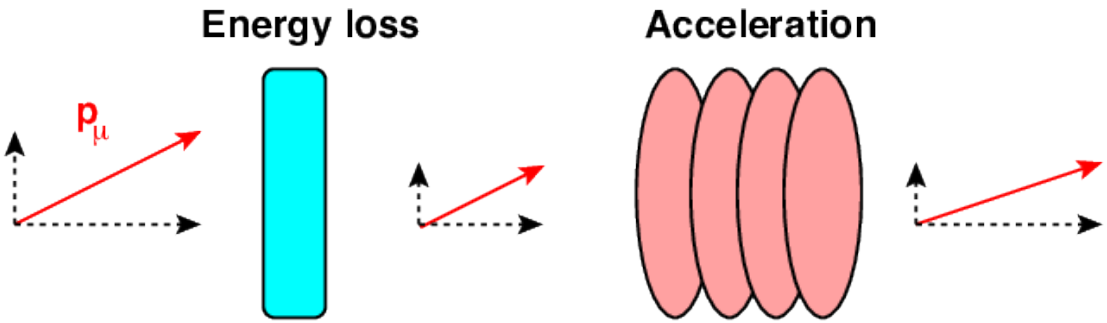
for the MICE Collaboration

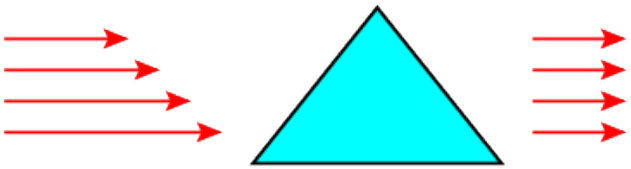
Illinois Institute of Technology

Ionization Cooling

- The only muon cooling scheme that appears practical within the muon lifetime (2.2μs)



- Cooling mainly transverse in a linear channel
- Longitudinal cooling requires momentum-dependent path-length through the energy absorbers



Ionization Cooling

Normalized transverse emittance ε of muon beam in solenoidal channel

$$\frac{d\varepsilon}{ds} \simeq -\frac{\left\langle \frac{dE}{ds} \right\rangle}{\beta^2 E} (\varepsilon - \varepsilon_0), \quad \varepsilon_0 \simeq \frac{0.875\text{MeV}}{\left\langle \frac{dE}{ds} \right\rangle X_0} \frac{\beta_\perp}{\beta}$$

ε_0: equilibrium emittance (multiple scattering $\sim$ cooling)

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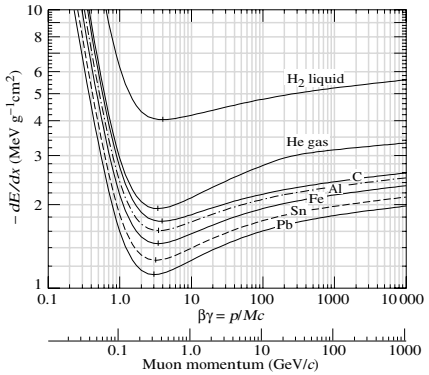
- Low muon momentum



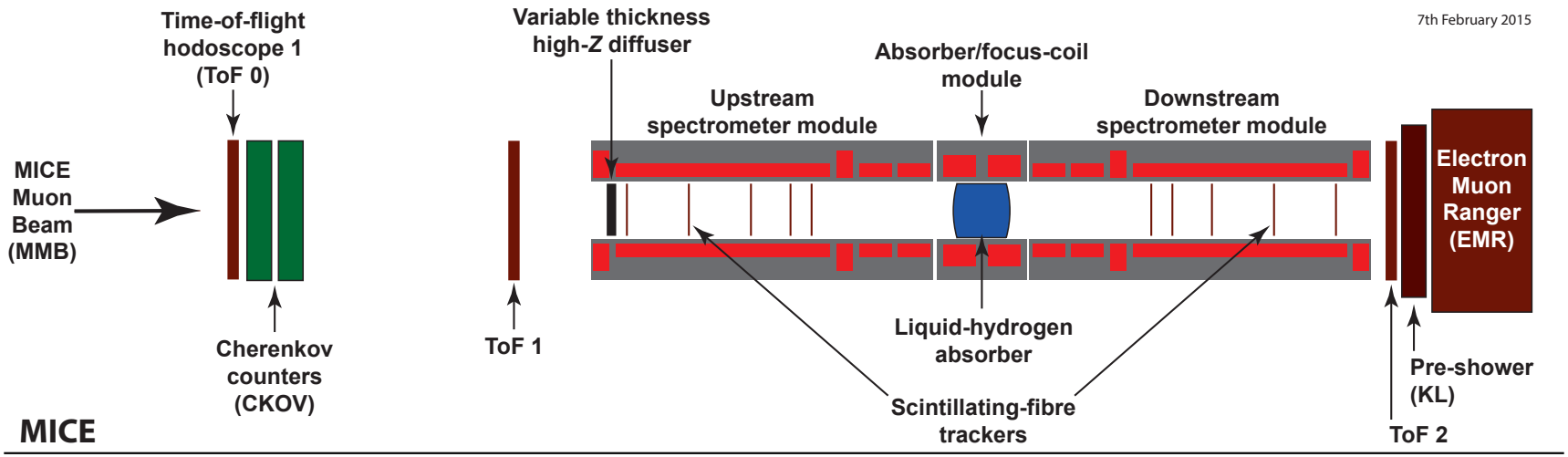
Muon Ionization Cooling Experiment

- Demonstration of ionization cooling in a setting relevant to muon accelerators
  - measure performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of cooling
  - study aspects critical to performance (multiple scattering, energy loss, emittance evolution)
  - validate design & simulation tools
- Concept
  - Track each muon before & after cooling hardware
  - Form "beam" in offline software
  - Designed for measuring relative change in emittance to 1%
  - Accelerator R&D in the form of a particle physics experiment

Status

- Beamline and detectors installed, operational, performance well understood
- Cooling channel components mostly installed and operational
- Data taking during ISIS user runs at Rutherford Appleton Lab

Present (Step IV) Configuration



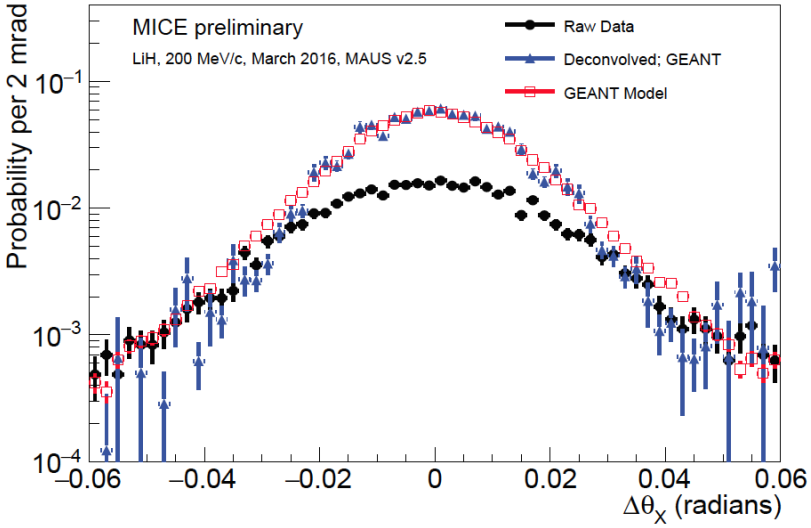
Detectors

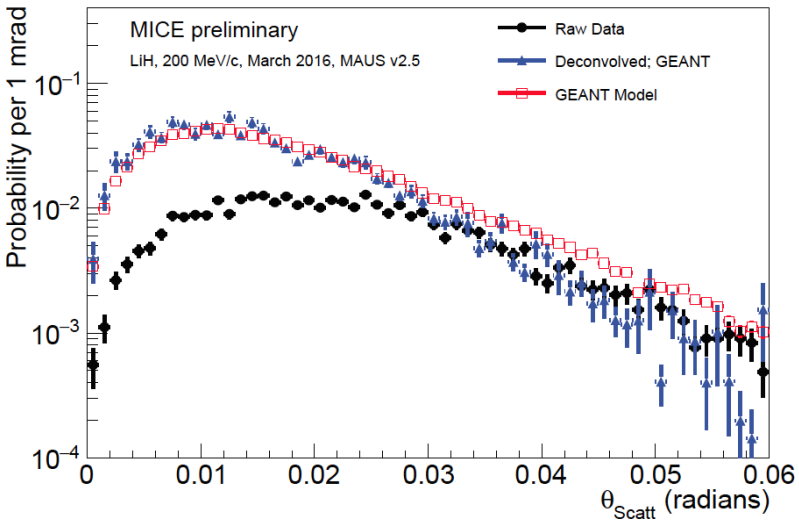
- Particle ID: reject beam contamination and muon decay
- Momentum: scintillating fiber trackers in spectrometer solenoids

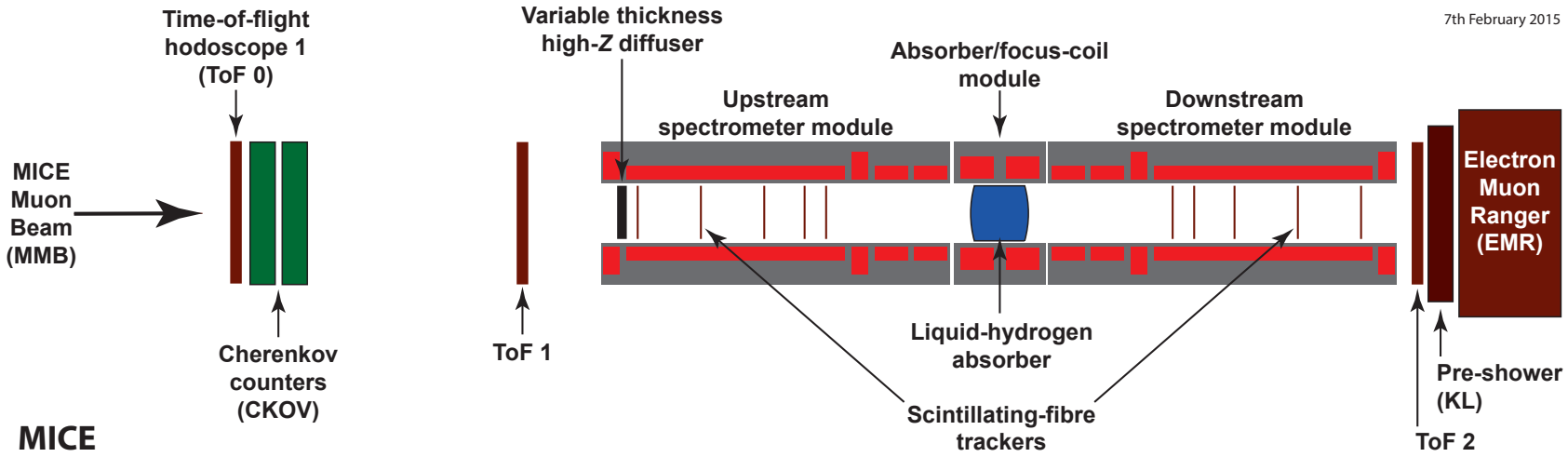
Beam manipulation

- Diffuser to vary input emittance
- Absorber (LiH, LH2) for cooling
- Superconducting solenoids for focusing and matching

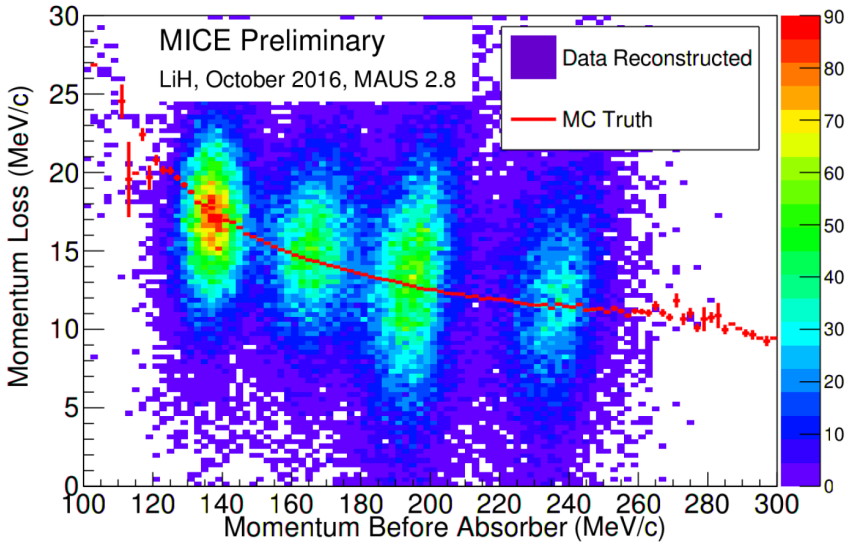
Step IV: Multiple Scattering (LiH, Xe)

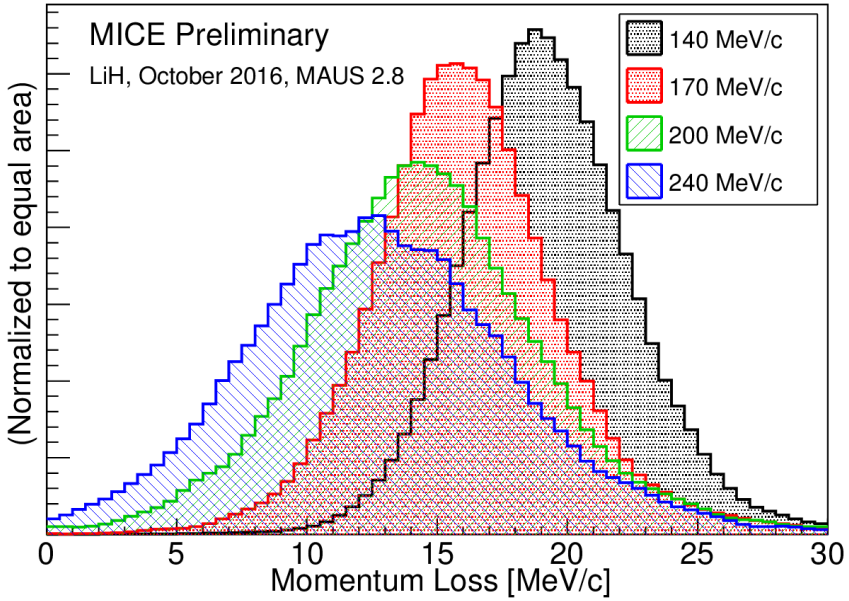


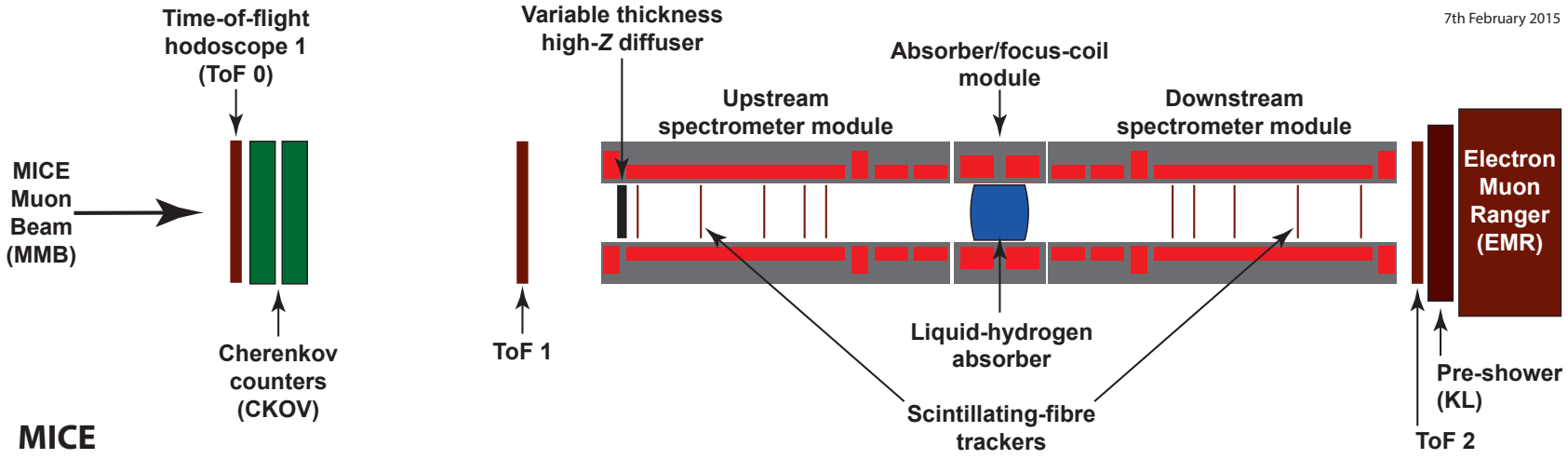




Step IV: Energy Loss







Emittance

Normalized RMS transverse 4D emittance ε

$$\varepsilon = \frac{1}{m_\mu}|\Sigma|$$

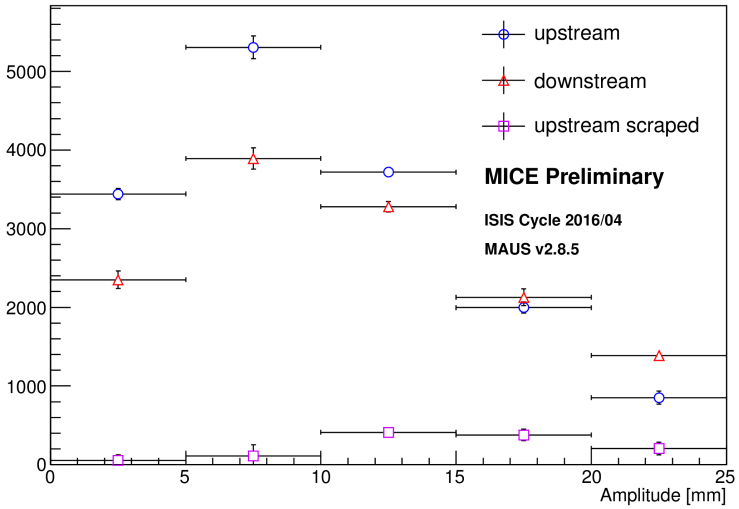
defined through phase space covariance matrix Σ

$$\Sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xp_x} & \sigma_{xy} & \sigma_{xp_y} \\ \sigma_{p_x x} & \sigma_{p_x p_x} & \sigma_{p_x y} & \sigma_{p_x p_y} \\ \sigma_{yx} & \sigma_{yp_x} & \sigma_{yy} & \sigma_{yp_y} \\ \sigma_{p_y x} & \sigma_{p_y p_x} & \sigma_{p_y y} & \sigma_{p_y p_y} \end{pmatrix}, \quad \sigma_{ab} = \langle (a - \langle a \rangle)(b - \langle b \rangle) \rangle$$

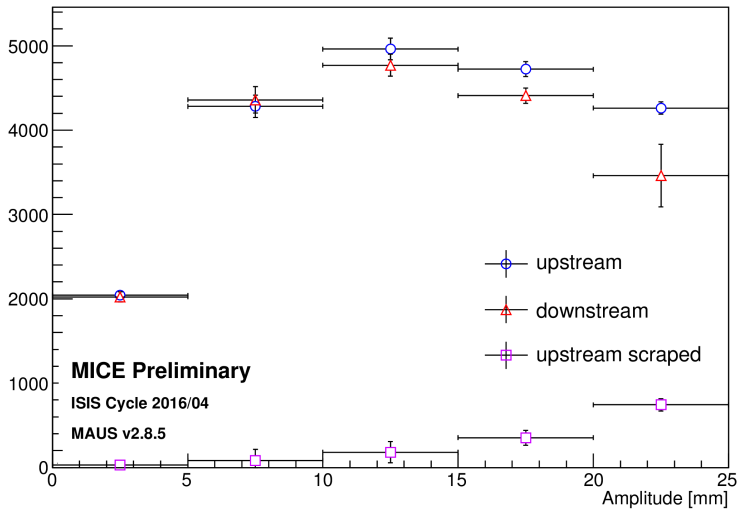
Strong coupling between transverse dimensions in solenoidal magnetic lattice.
Single particle amplitude and phase space density more useful in the presence of nonlinear effects.

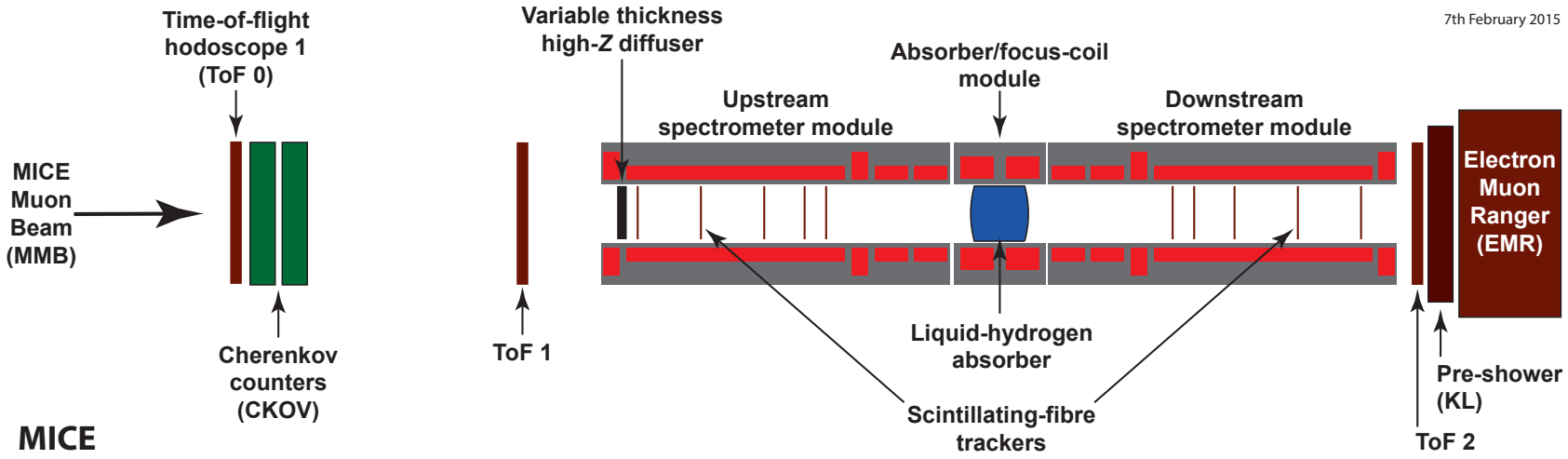
Step IV: Emittance Evolution (Amplitude)

3 mm beam heated

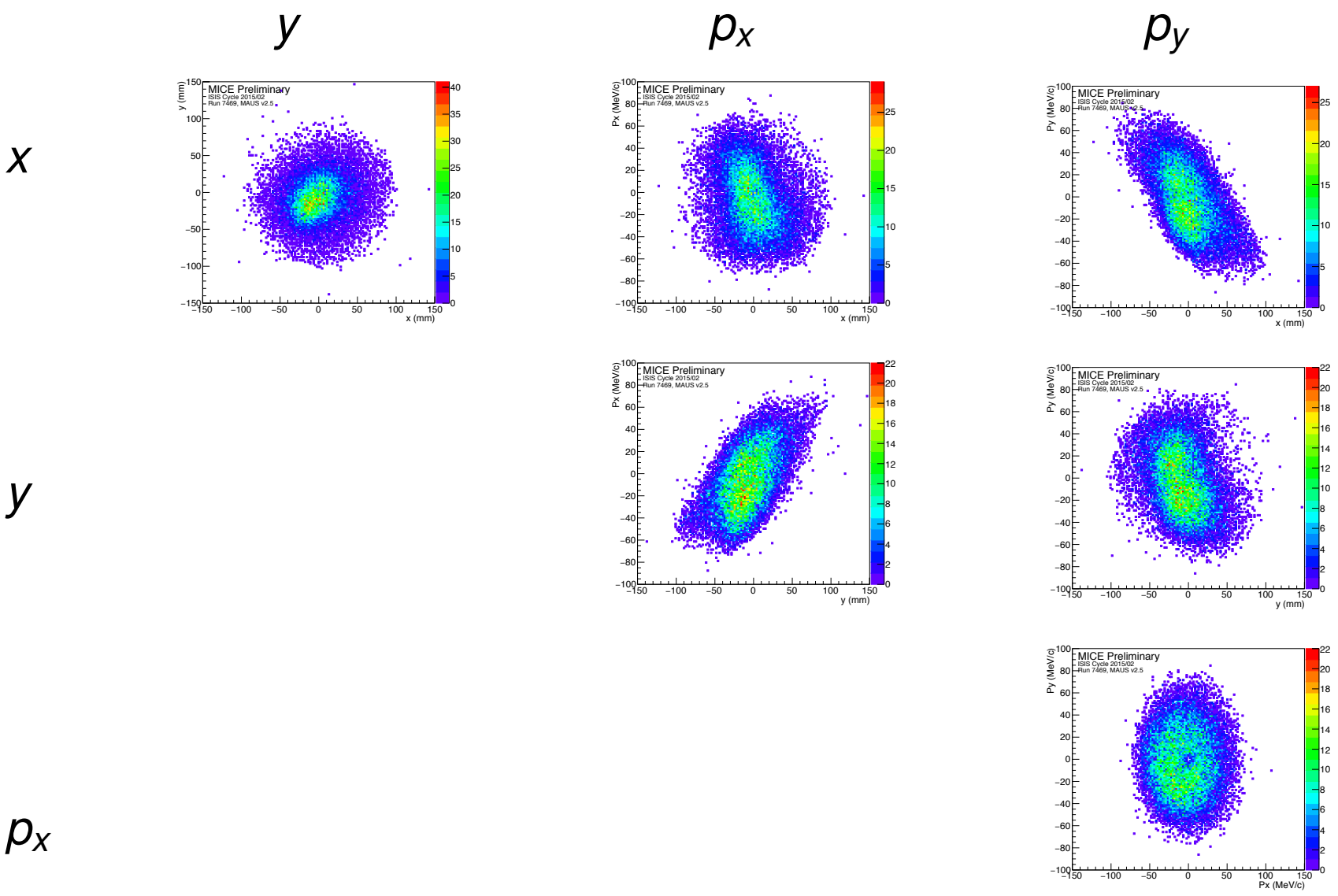


6 mm beam (ε_0) preserved

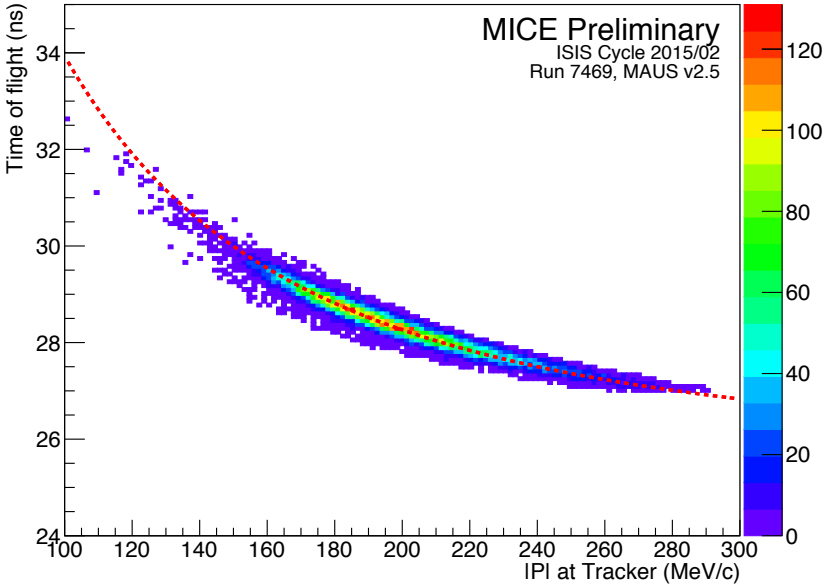


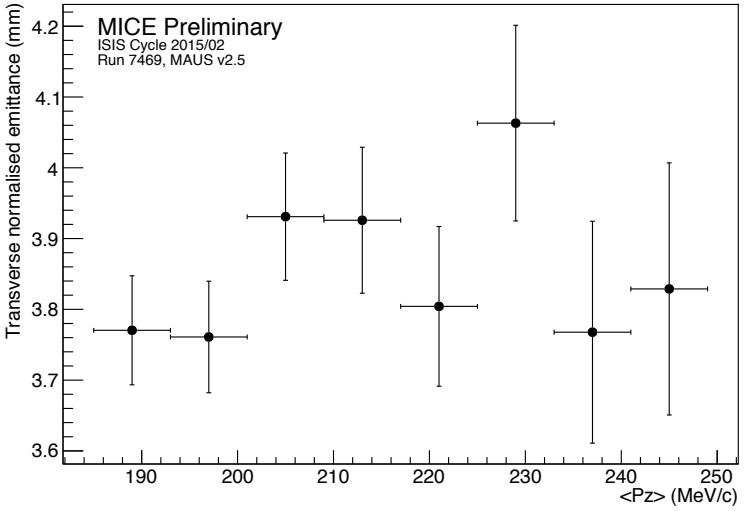


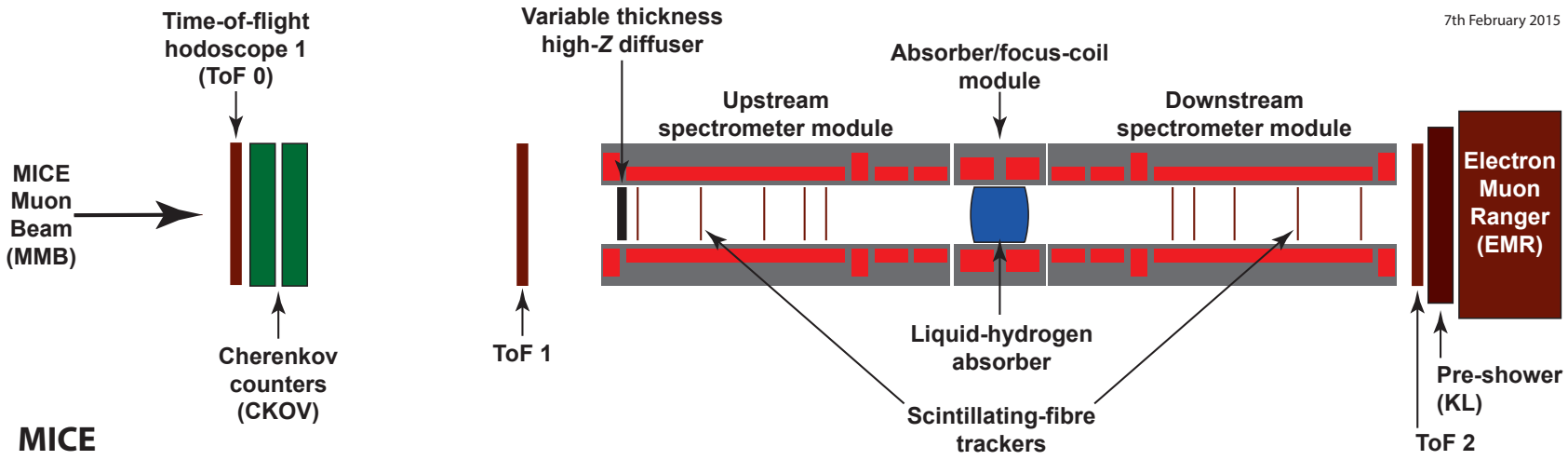
Emittance Evolution (Phase Space)



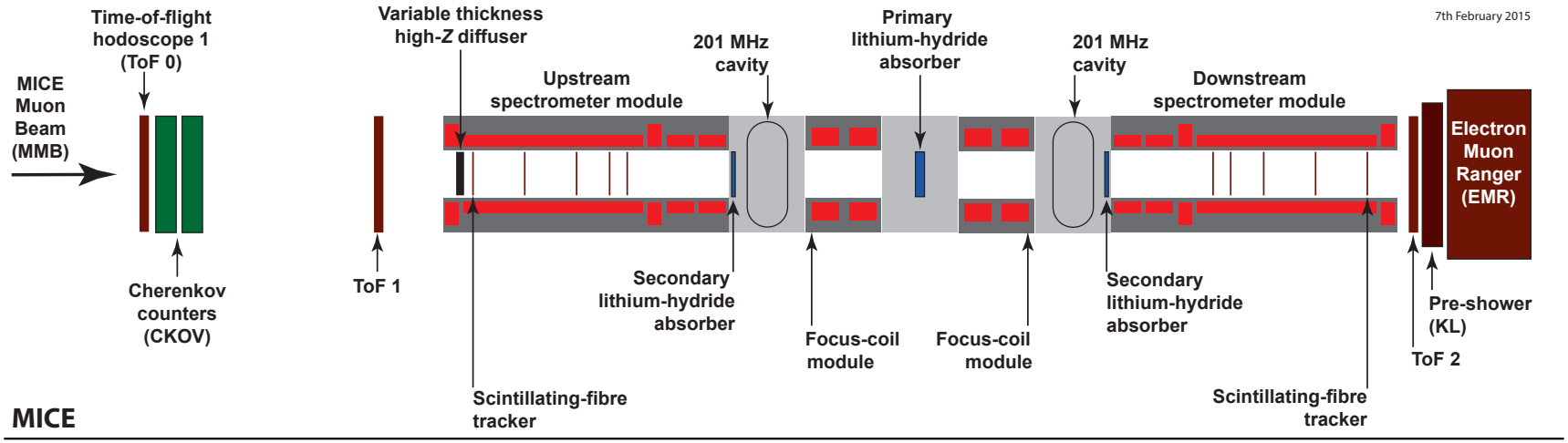
Step IV: Emittance Measurement





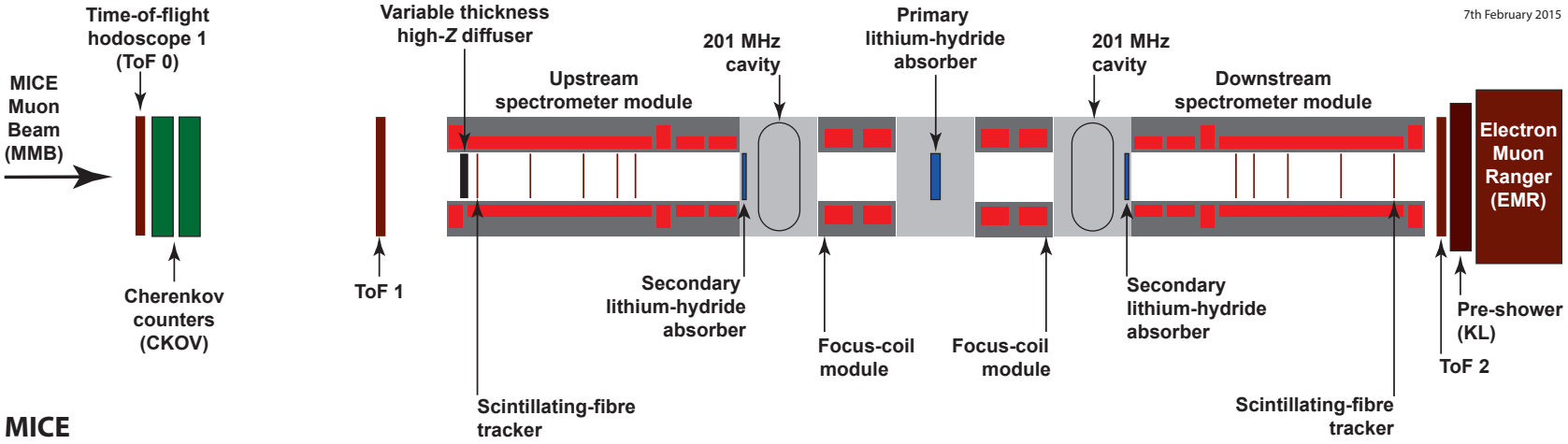


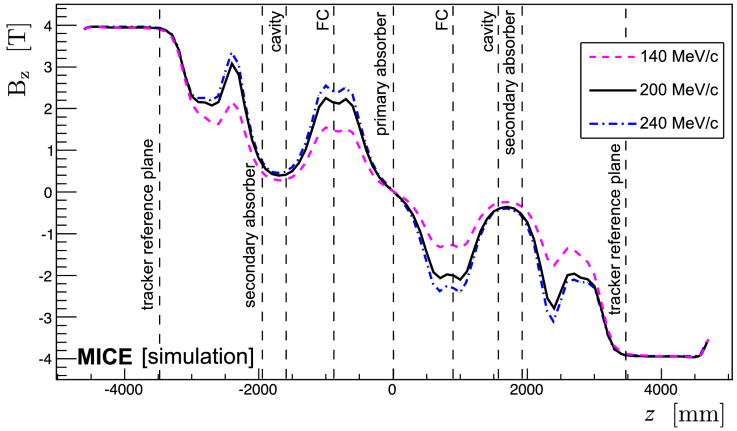
Cooling DEMO with Acceleration

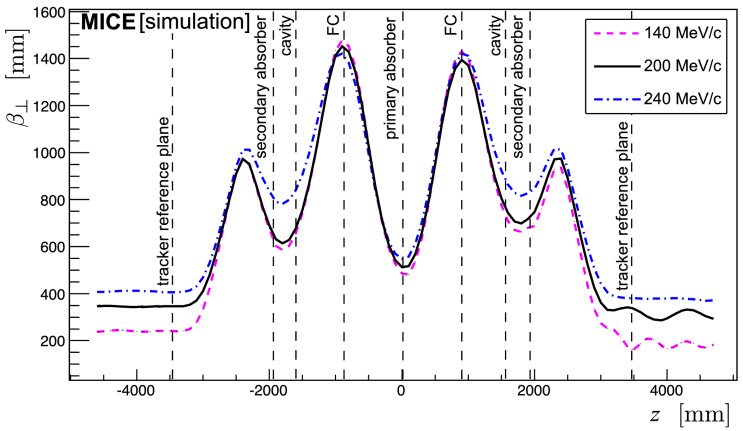


- Same particle ID detectors
- Same primary LiH absorber
- Same magnets
- RF cavities for acceleration
- Secondary LiH absorbers
- Additional Focus Coil Module

Cooling DEMO with Acceleration







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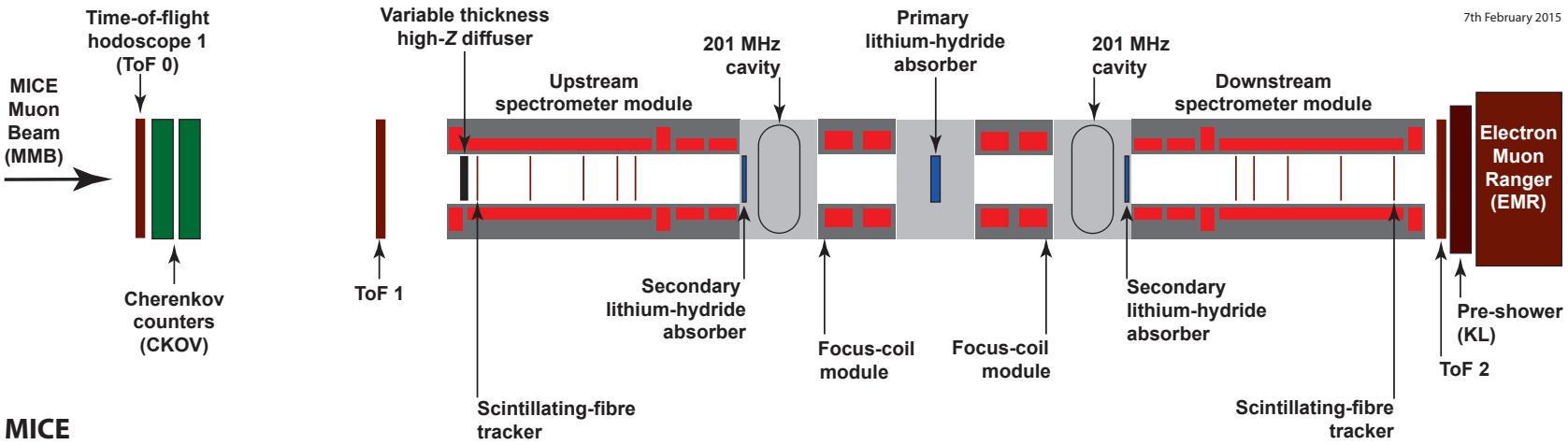

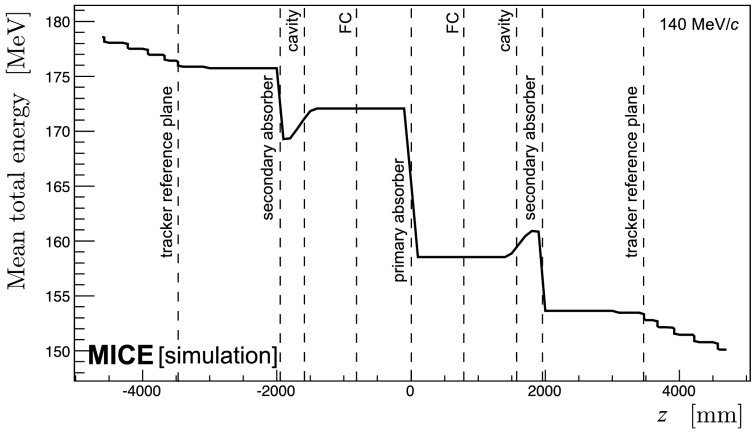

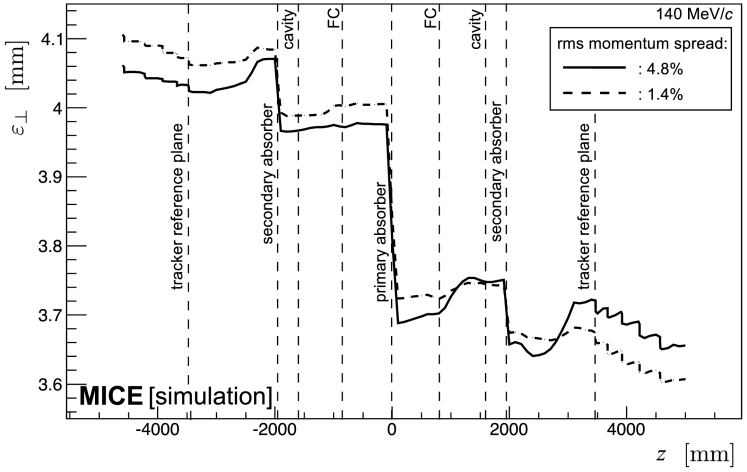

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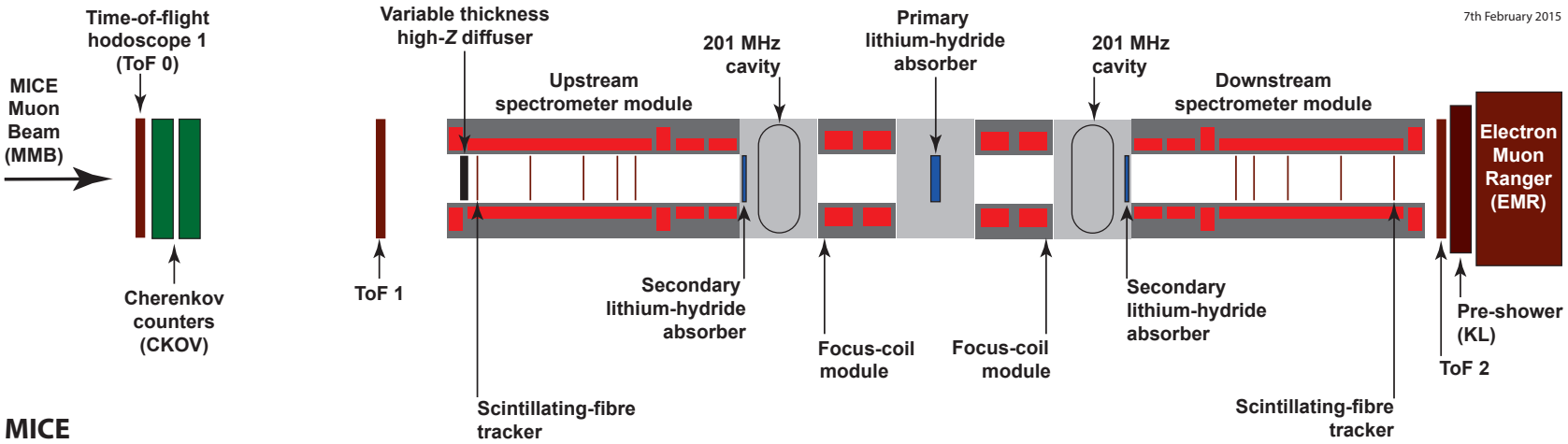

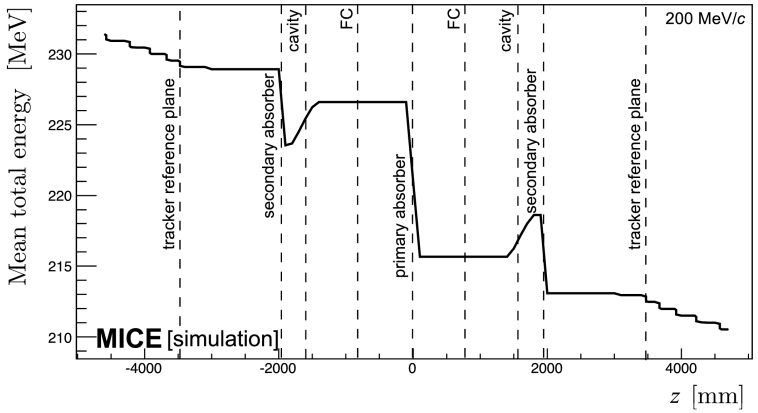

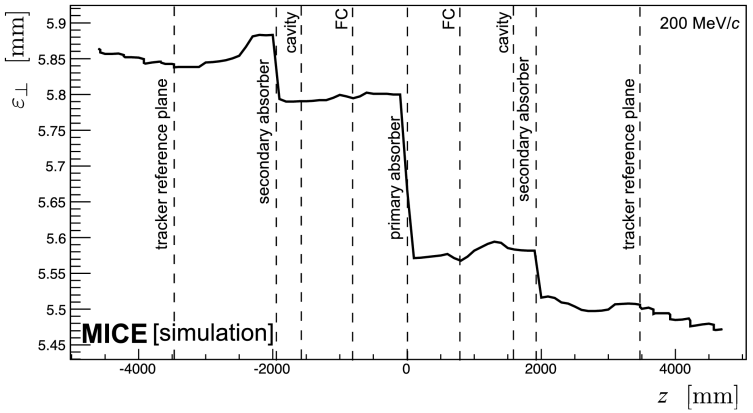

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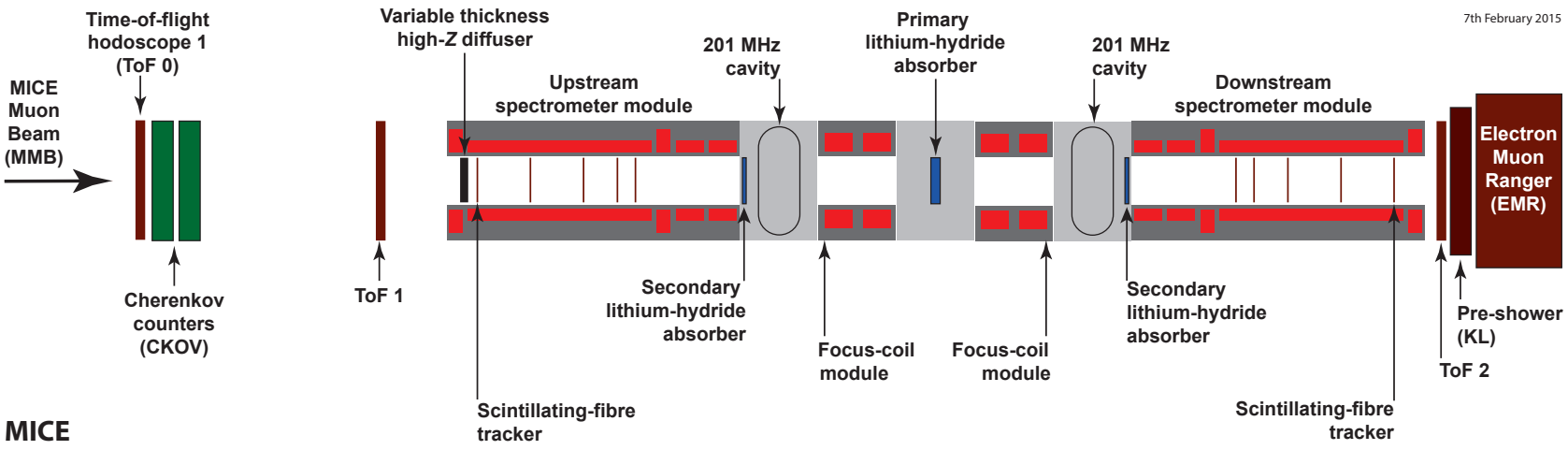

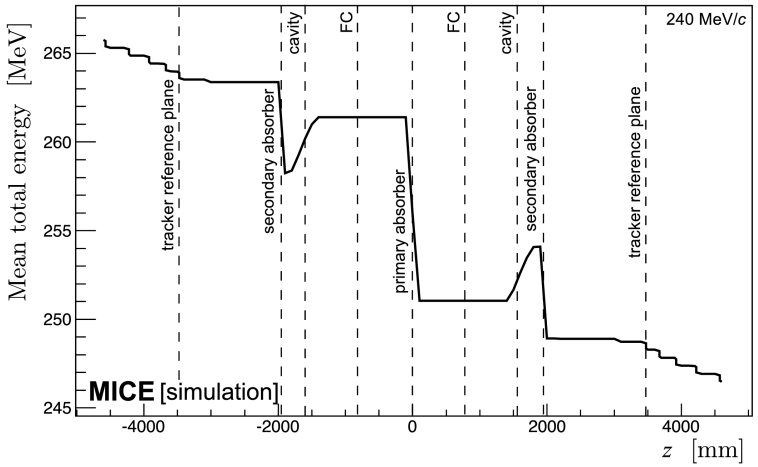

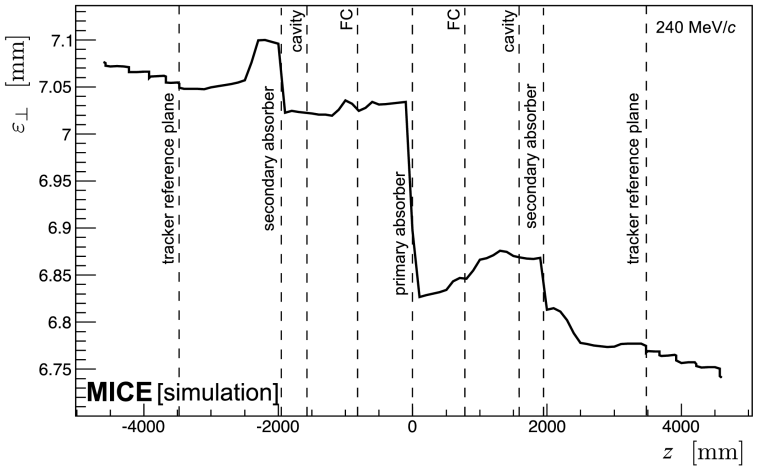

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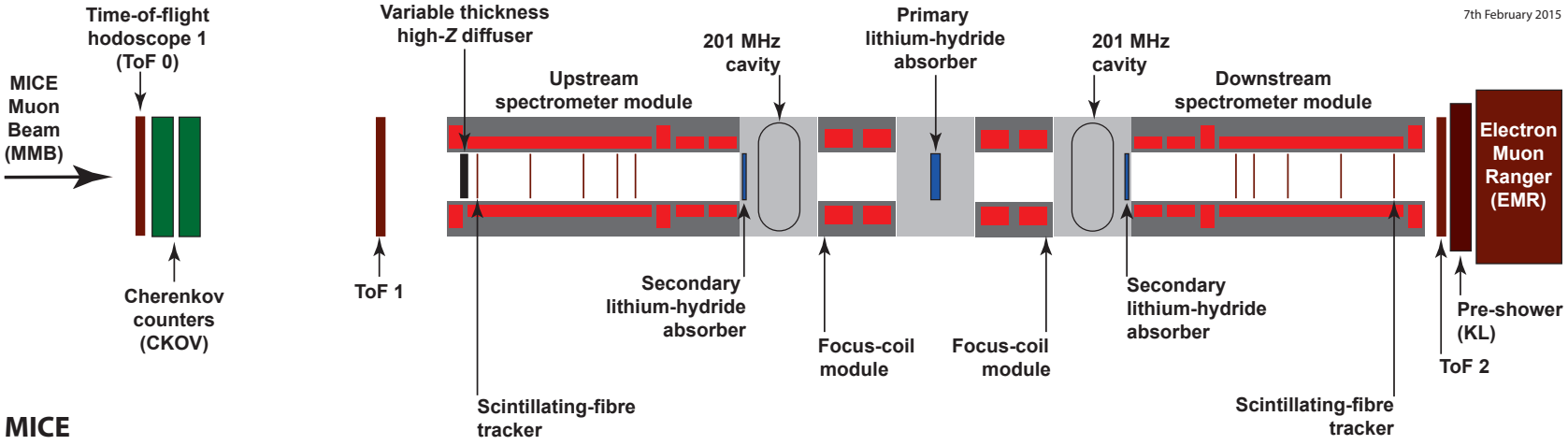
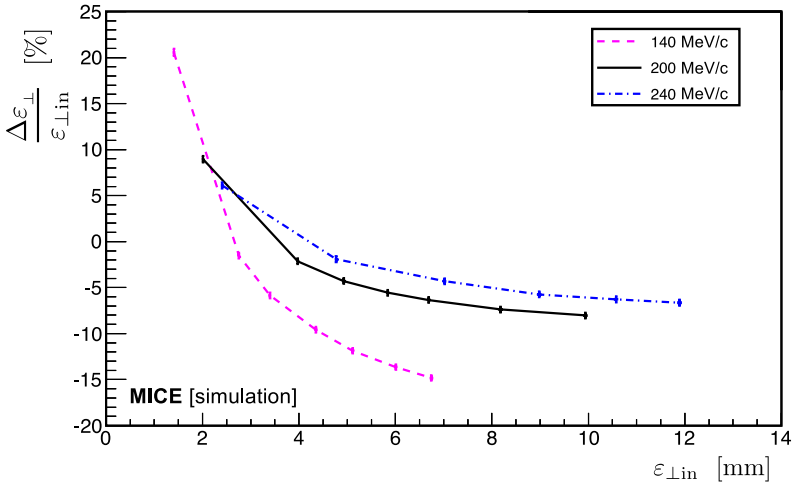
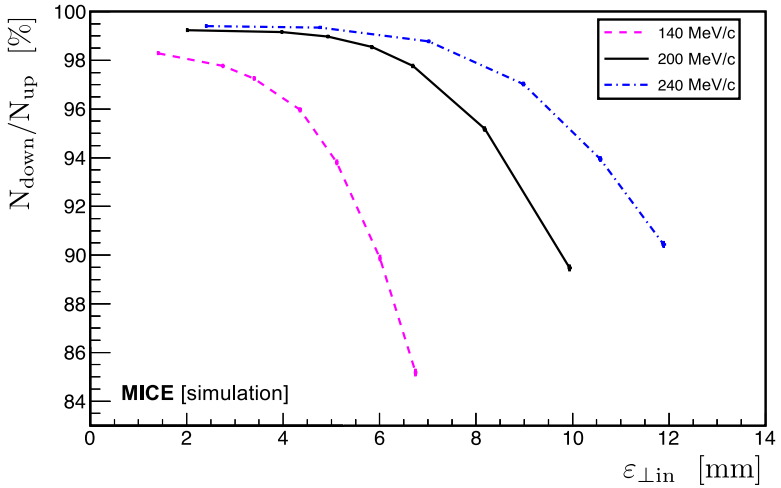


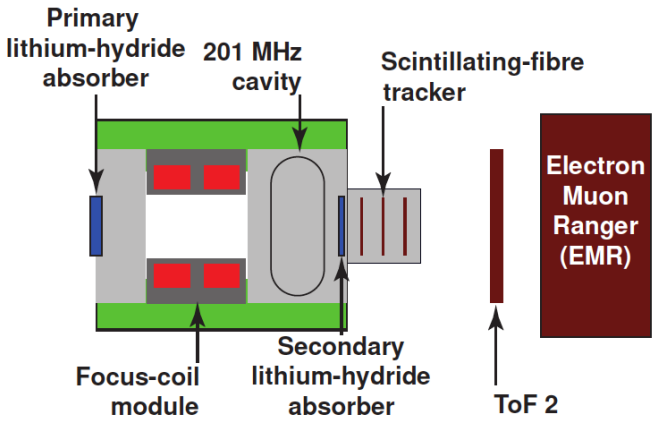


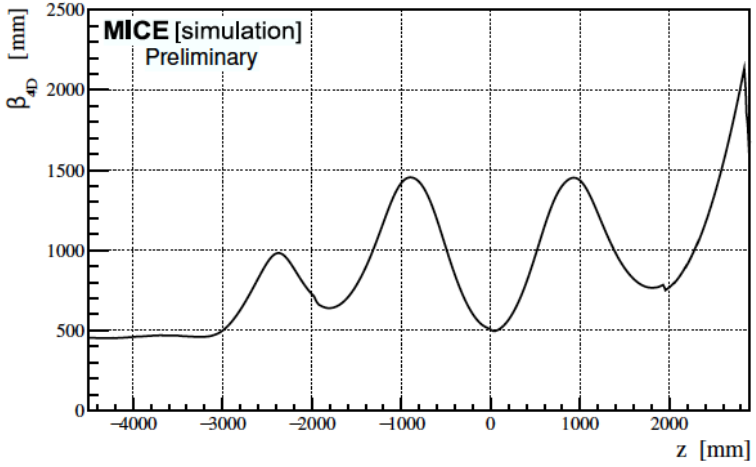


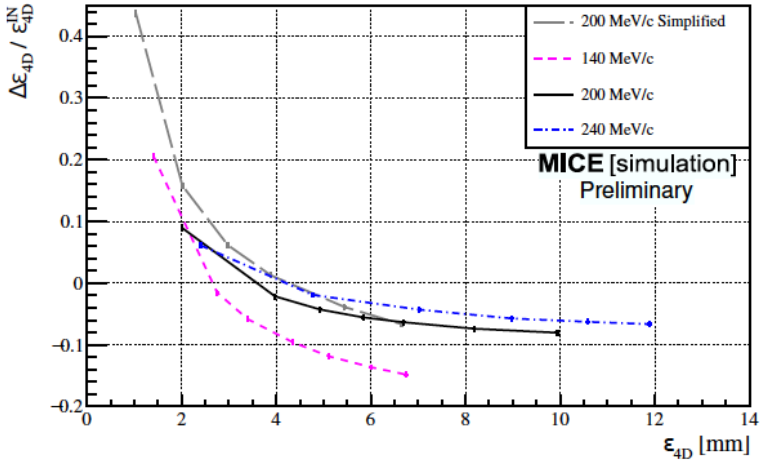
Simplified Configuration

Remove downstream SS, KL; install shorter tracker,

- fits inside existing shielding
- uses existing hardware
- reduced transmission at high emittance
- reconstruct momentum with SciFi tracker+EMR







Status and Outlook

- Infrastructure & equipment
  - Beamline and detectors performing well
  - Cooling channel operational
- Data
  - Simulation, reconstruction, analysis tools validated
  - LiH scattering program complete
  - Emittance evolution with LiH, various initial emittance, beam momentum and magnetic lattice settings
  - LH2 absorber to be used in next run (Sep-Oct 2017)
  - Wedge absorber available to study 6D emittance evolution
- Cooling demonstration with RF acceleration
  - RF modules complete
  - Installation at RAL not funded
  - Exploring options (IHEP Protvino)